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OUTER ATMOSPHERES OF GIANT AND SUPERGIANT STARS

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ABSTRACT

The properties of the chromospheres, transition regions and coronae of cool evolved stars are reviewed based primarily on recent ultraviolet and X-ray studies. Recent determinations of mass loss rates using new observational techniques in the ultraviolet and radio spectral regions are discussed and observations indicating general atmospheric motions are considered. The techniques available for the quantitative modeling of these atmospheres are outlined and recent results discussed. Finally our current rudimentary understanding of the evolution of these outer atmospheres and its causes are considered.

I. INTRODUCTION

The range of astrophysical research implied by the title of this review is so large that the subject matter must be restricted to fit both the time and space available to me. The review is therefore restricted to:

a) single, cool (spectral-type F-M), evolved stars,

b) the chromospheres, transition regions and coronae of these stars (i.e. that portion of the stellar atmosphere outside the photosphere), and

c) primarily to advances made during the last two or three years using the International Ultraviolet Explorer (IUE) satellite in the ultraviolet spectral region (1200-3200 Å) and the Einstein satellite in the X-ray spectral region (3-60 Å).

In recent years several excellent reviews have been written on the general topic of stellar chromospheres and coronae and I refer the reader to Linsky (1980, 1982), Dupree (1981a) and Jordan (1983) for a wider coverage of this research area, which has flourished with the general availability of ultraviolet and X-ray data. Many new and exciting results are emerging from this research allowing for a far deeper understanding of these outer atmospheres than has ever been possible before. Detailed studies of many chromospheric and transition region phenomena require observations at the limits of current instrumental capabilities in terms of both length of observation and required accuracy. The work currently being done is creating the basis of a new research area and laying the foundation for studies involving future space observatories.

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II. OBSERVED PROPERTIES OF GIANTS

Observations of giant stars made during the first year of IUE operations clearly showed that two distinct forms of ultraviolet spectrum are seen from these stars (Linsky and Haisch 1979; Brown, Jordan and Wilson 1979; Dupree et al. 1979). Giants with spectral types earlier than K1 have ultraviolet spectra similar to those of dwarf stars in which most of the lines are formed by collisional excitation in an atmosphere containing material at temperatures from ~6000 K (Mg II resonance doublet) to over 10^5 K (C IV and N V resonance lines). X-ray observations by the Einstein satellite showed that these stars also possess coronal regions with temperatures up to $\sim 10^7$ K (Vaiana et al. 1981; Ayres et al. 1981; Haisch and Simon 1982). On the other hand, giants of spectral type K1 and later show no ultraviolet emission lines formed at temperatures much greater than 10^4 K nor do these stars show X-ray emission. Many of the emission lines seen from these stars are formed by fluorescence, e.g., the S I 1295, 1296 Å lines pumped by the O I resonance lines (Brown and Jordan 1980), and other radiative processes rather than collisional processes. A fuller review of radiative processes in the atmospheres of such stars is given by Jordan and Judge (1983). A typical example of each type of spectrum is shown in Figure 1.

Observations of the profiles of the Mg II resonance doublet at 2796 and 2803 Å have shown that a systematic change also occurs in the asymmetry of these optically thick, self-absorbed line profiles (Stencel and Mullan 1980). Stars showing coronal emission tend to have a stronger blue wing, while the stars showing only cool emission lines have a stronger red wing and this is interpreted as the presence of an accelerating outflowing stellar wind from the stars with strong red asymmetries (cf. Hummer and Rybicki, 1968). However, when considering individual stars, especially distant high luminosity stars, the influence of interstellar absorption is severe and can totally alter the observed line profile (Bohm-Vitense 1981). Stencel et al. (1981) showed that stars with outflowing winds have extended atmospheres while models of coronal stars indicate an essentially solar-like structure.

Much controversy has ensued concerning the nature and cause of the division between the two types of atmospheric structure implied by the IUE observations. Linsky and Haisch (1979) first proposed the presence of a <u>sharp</u> dividing line in the HR diagram between stars showing coronal and non-coronal structure, i.e., through the presence of C IV emission. Various authors proposed that the change was more gradual in terms of line strengths and other atmospheric properties (Jordan and Brown 1981; Reimers 1981; Hartmann, Dupree and Raymond 1982) while others have sought to strengthen the argument for a sharp division (e.g. Simon, Linsky and Stencel 1982). Baliunas, Hartmann and Dupree (1983) showed that the C IV emission line fluxes of the four Hyades K0 giants were not equal but differed by significant amounts even when differing distances were taken into account. The present situation for giants is that while a large range in terms of line strength is seen near

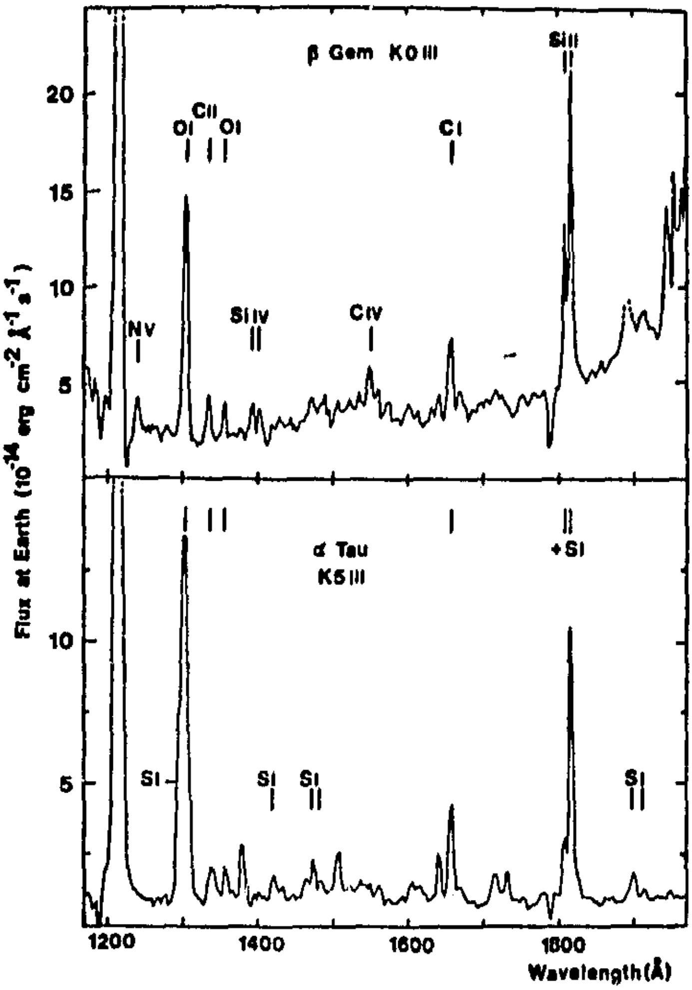

Fig. 1. The low dispersion IUE spectra of β Gem, a coronal giant, and α Tau, a star with only a cool extended chromosphere. The β Gem spectrum is from a single 120 minute exposure while the α Tau spectrum is the summation of a series of spectra, the longest having an exposure time of 150 minutes. The upper limit on the C IV emission is $\sim 2.5 \times 10^{-14}$ ergs cm^{-2} s^{-1} with the noise level on the combined spectrum being slightly less than but of the same order as this value. These spectra were reduced using the Oxford University ICL 2980 computer and the methods described by Brown and Jordan (1981).

the dividing line, it seems that all giant stars, as they evolve up the red giant branch, suffer a fundamental change in outer atmospheric structure and this change occurs near spectral type K1. Therefore the position of a giant star in the HR diagram, i.e., its luminosity and temperature, are major factors in determining its outer atmospheric structure but the actual level of emission is severely affected by an as yet ill-defined third parameter.

III. OBSERVED PROPERTIES OF BRIGHT GIANTS AND SUPERGIANTS

While the coronal/non-coronal dividing line of Linsky and Haisch still seems relevant for giants, this is not true for more luminous stars where the situation is far more complicated. Hartmann, Dupree and Raymond (1981) showed that the star α TrA (K4 II) has C IV emission although it lies considerably to the right of the Linsky-Haisch dividing line. Subsequently, Reimers (1982) identified three further K bright giants which showed C IV emission (ι Aur, θ Her and δ TrA) and Hartmann et al. (1983), in addition to confirming the findings of Reimers, showed that γ Aql has similar properties. These stars are known as hybrid stars and are identified by the presence of C IV emission and high velocity blue-shifted absorption components in the Mg II and Ca II resonance doublets presumed to be caused by an outflowing wind. It is the simultaneous presence of transition region material and a stellar wind which makes these objects so interesting and important in understanding the transition between coronal-type structure and the cool, extended chromospheres of cooler stars. The early G supergiants, α and β Aqr, also show the properties of hybrid stars and represent the supergiant equivalents of the K bright giant hybrid stars (Hartmann, Dupree and Raymond 1980). (Early K supergiants show only cool extended chromospheres.) No known hybrid star has yet been detected as an X-ray source.

The hybrid stars are variable both in TR line strength and in the velocity and mass flux of their winds as indicated by the Mg II absorption components. The variability of C IV line strength may be responsible in part for earlier arguments as to whether or not particular stars are hybrid stars. Hartmann et al. (1983) have shown that over a year the velocity of the α TrA Mg II absorption component increased from -84 to -180 km s^{-1}. Also, Drake, Brown and Linsky (1983) find that the high velocity blue-shifted Mg II components of hybrid stars have radial velocities that show a greater scatter than those of the narrower low velocity absorption components. The variability and breadth of the high velocity features suggest that they are formed in a high-velocity rather turbulent stellar wind. The low-velocity absorption features, on the other hand, are most probably formed in the interstellar medium.

In the past, there has been much discussion as to the nature of the atmospheric structure of hybrid stars. Hartmann, Dupree and Raymond (1981) proposed that the TR emission lines were formed in the outflowing wind and that the heating required for this might be derived from deposition of energy by Alfvén waves. Linsky (1982), on the other hand, proposed that the structure had two components, namely, magnetically confined TR material and a cooler outflowing stellar wind. The present situation (see for instance, Hartmann et al. 1983) seems to be that the observational evidence suggests that the C IV resonance and C III and Si III intersystem lines are not formed in the stellar wind and that the temperature of the wind is no more than a few $\times 10^4$ K.

IV. MASS LOSS AND MASS LOSS RATES

Mass loss is an important process among cool giants and supergiants since the onset of mass loss is intimately related to the significant changes in atmospheric structure already noted. Accurate determination of mass loss rates is important in establishing what effect the observed mass loss will have on the evolution of these stars. Drake and Linsky (1983c) discuss in some detail new methods for the determination of mass loss rates and reference to those areas shall therefore be brief here. Recent reviews by Castor (1981), Dupree (1981b), Reimers (1981) and Linsky (1981) discuss in depth the nature of and possible mechanisms causing mass loss in cool stars; here only new methods and subsequent results will be discussed.

A. Ultraviolet Observations

Observations of stellar winds in the ultraviolet are superior to optical studies because lines of ions which are dominant species can be studied. This removes many of the uncertain assumptions necessary in the optical derivation of mass loss rates.

The first observations which definitely showed that mass was lost from stars were those of the G giant companion of α Her by Deutsch (1956) where absorption lines from the wind of the M5 bright giant primary were seen in the spectrum of the companion. Such observations allow the use of the companion as a probe of the stellar wind structure and this technique has been elegantly used by Che, Hempe and Reimers (1983) in the ultraviolet to study the winds of the K supergiant primaries of ζ Aurigae-type binary systems. Che et al. modeled the equivalent widths and line profiles of Fe II, Si II and S II lines seen in the B dwarf companion's spectra using a non-spherically symmetric, three-dimensional radiative transfer code. Mass loss rates and wind velocities were determined for ζ Aur, 32 Cyg and 31 Cyg. The mass loss rates fell in the range 0.6-2.8 (-8) $M_\odot$ yr^{-1} with wind velocities of 30-80 km s^{-1}.

Mass loss rates can also be determined by modeling the Mg II and, less importantly, Ca II resonance doublets. The Mg II lines have the advantages of being formed higher in the chromosphere than the Ca II lines due to their greater optical depth and of being seen against a lower photospheric background. The derivation of mass loss rates from observations of these lines is not a simple calculation nor can unique results be guaranteed. Drake and Linsky (1983a) have developed a co-moving frame, spherical symmetry, partial redistribution (PRD) radiative transfer code which they have used to model the Mg II lines of the K0 giant α Boo. The mass loss rate determined is 1(-10) $M_\odot$ yr^{-1} with a velocity of 40 km s^{-1}.

B. Radio Observations

The Very Large Array (VLA) radio telescope has the ability to detect cool giant and supergiant stars due to the free-free emission originating from their partially or fully ionized stellar winds. Drake and Linsky (1983c) present a table of derived mass loss rates for the sample of cool stars so far studied with the VLA. Of particular importance is the probable detection of emission from K giants for the first time (α Boo and β Gem). To illustrate the type of data which the VLA can provide, a 6 cm VLA map of the region around α Her (from Drake and Linsky 1983b) is shown in Figure 2.

The most significant fact to be noted from Table 1 of Drake and Linsky (1983c) is how small the newly derived mass loss rates are compared with previous results. For the rate derived from radio observations there is always the possibility that the wind is predominently neutral, in which case the radio observations place severe upper limits on the fractional ionization. The upper limit shown for the mass loss rate of the hybrid star ι Aur is smaller than previously quoted values which were used to compute Alfvén-wave driven wind models for such stars (Hartmann, Dupree and Raymond 1981).

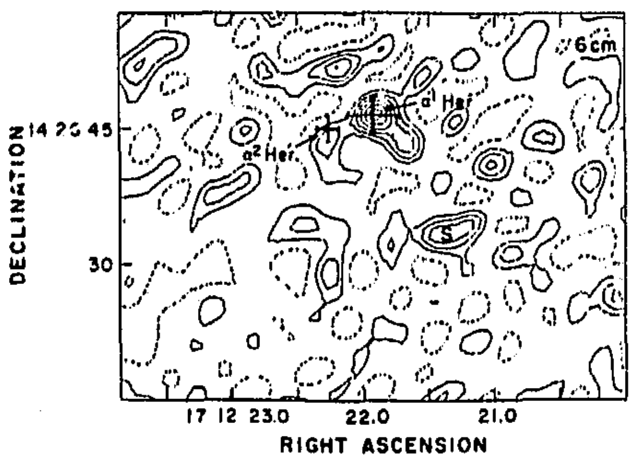

Fig. 2. A VLA 6 cm (4885 MHz) map of the region surrounding the binary star α Her. The base contour level (the first solid contour) is equivalent to the r.m.s. noise level. The optical positions of α^1 Her and α^2 Her are indicated, but note that the uncertainties in these positions are much less than the crosses shown. A serendipitous source (S) is also indicated. α^2 Her has a flux density of 1.2 ± 0.2 mJy (from Drake and Linsky 1983b).

V. ATOMSPHERIC MOTIONS

In addition to the information that IUE spectra provide concerning the outflowing winds of cool stars, other effects of atmospheric motions are detectable. Ayres et al. (1983) and Brown et al. (1983) have shown that in the IUE spectra of a wide variety of coronal stars, ranging from dwarf stars to the supergiant β Dra, systematic wavelength shifts are seen between transition region and chromospheric emission lines. The shift is in the sense that the transition region lines are red shifted with respect to the chromospheric lines.

This phenomenon is best illustrated by observations of α Aur (Capella) and β Dra. Ayres (1983) obtained a series of wavelength calibrated high dispersion IUE spectra close to conjunction of the Capella binary system. These spectra were then co-added to give the results shown in Figure 3. The zero velocity represents the rest velocity of the system and therefore at conjunction the rest velocities of both stellar photospheres. The striking feature is that all the emission lines, even the chromospheric lines are red shifted. Before examining the other features of this diagram it is best to consider β Dra, which Brown et al. (1983) have studied in detail. From the observed line widths, profiles and ratios of the C IV and Si IV resonance doublets, these lines are seen to be optically thick and asymmetric to

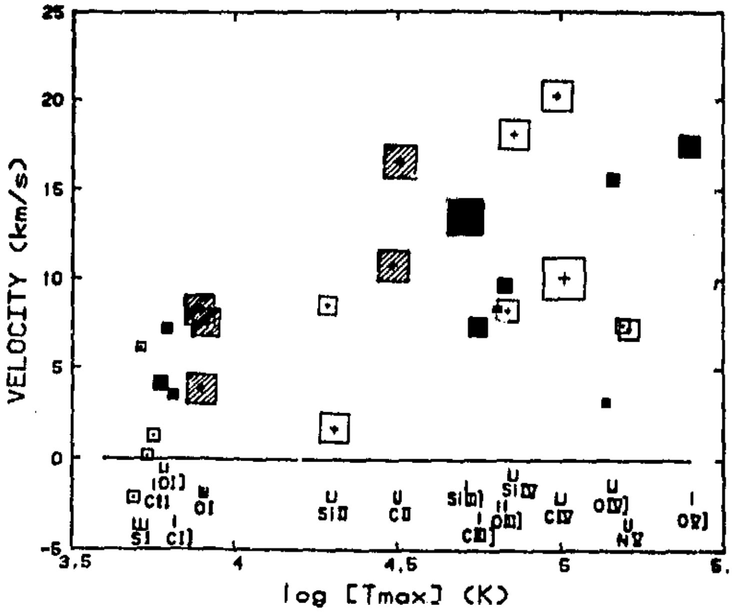

Fig. 3. The observed line centroid velocities for a range of emission lines from the Capella binary system at conjunction. Open symbols indicate lines which have uncertain optical thickness, solid symbols lines which are definitely optically thin and hatched symbols lines which are definitely optically thick (from Ayres 1983).

the red, resulting in the measured redshifts. The observed shifts for these lines are therefore most likely due to optically thick line formation in a turbulent medium containing accelerating upflows and/or decelerating downflows. This conclusion also applies to other optically thick lines such as the C II and O I resonance lines. Hence, simple interpretation of the line shift data is best restricted to the optically thin intersystem lines which are redshifted by +8 ± 4 (1σ) km s^{-1} in β Dra and also by a similar amount in α Aur as can be seen from Figure 3. These values are near the limits possible using IUE and clearly confirmation of such results by future higher-quality measurements is desirable. However at face value these shifts indicate a net excess of emission from downward moving material over that from material moving upward.

VI. ATMOSPHERIC MODELING

A. Modeling Techniques

As might be expected from the very different spectra of coronal and noncoronal stars, the techniques used to calculate atmospheric models are different for the two groups of stars.

For coronal stars the two techniques which have been widely used are emission measure analysis and radiative transfer modeling of the Mg II and Ca II resonance lines. Emission measure analysis can be used to model the portion of the outer atmosphere at temperatures $\gtrsim 10^4$ K where hydrogen is predominantly ionized. This type of analysis was originally developed for solar work (Pottasch 1964; Jordan and Wilson 1971) and its general application to stellar chromospheres and coronae has been discussed in detail by Jordan and Brown (1981). The emission measure, E_m, is $\int_{\Delta H} N_e^2 dh$ where ΔH is the region of line formation and is related to the total surface flux of a collisionally-excited, effectively-thin emission line, using our current formalism, by

$$F_* = \frac{8.6\times10^{-22}}{\lambda(\mathrm{cm})} \frac{\Omega_{12}}{\omega_1} \frac{N_E}{N_H} \frac{N_1}{N_{ion}} g(T_m) \int_{\Delta H} N_e^2 dh \quad .$$

Here Ω_{12} is the averaged collision strength, ω_1 is the statistical weight of the lower level, N_E/N_H is the elmental abundance, N_1/N_{ion} is the population of the lower level and $g(T_m)$ is the value at peak ion population of the temperature-dependent function

$$g(T) = T_e^{-1/2} \exp(-W_{12}/kT_e) \frac{N_{ion}}{N_E} \quad .$$

W_{12} is the excitation energy and all other symbols have their usual meaning.

From the emission measures of individual lines a mean emission measure distribution is derived and then plane-parallel atmospheric models can be computed in

hydrostatic equilibrium using

$$dT_e/dh = P_e^2/[2.0\ E_m(T_e)T_0]$$

and

$$dP_e/dh = -7.14 \times 10^{-9}\ P_e g_*/T_e$$

where P_e is the scaled pressure (N_eT_e) and g_* is the stellar surface gravity.

The alternative modeling method for coronal stars is to use the Mg II and, less importantly, Ca II resonance line profiles to determine the chromospheric structure by means of partial-redistribution (PRD) line transfer codes and then to derive the transition region structure by matching the line fluxes of lines such as the Si IV, C IV, and N V resonance lines. This method can also be applied to noncoronal stars with extended atmospheres although in this case the systematic outflow of the stellar wind must be explicitly included in the calculation. In order to produce reasonably unique results from modeling the Mg II resonance line profiles, constraints on the atmospheric pressure must be obtained from density sensitive line ratios. (This is also true for emission measure analysis.)

The estimation of electron densities from line ratios is a critical step in the modeling process. For coronal stars the most useful line ratios are between (i) the intersystem lines of C III 1909 Å and Si III 1892 Å, although in this case the original density calibration of Cook and Nicholas (1979) must be corrected for the new Si III atomic data (Baluja, Burke and Kingston 1980, 1981), and (ii) the members of the O IV intersystem multiplet at 1401, 1405 and 1407 Å (Nussbaumer and Storey 1982). For stars with cool extended chromospheres the C II intersystem multiplet near 2325 Å provides the best density estimates (Stencel et al. 1981).

A further method for calculating atmospheric models of cool extended chromospheres involves the study of the ratios of lines of differing opacity which originate from the same upper level. In the situation where one line is optically thick and the other is not, Jordan (1967) showed that the opacity in the optically thick line can be determined and a mass column density derived. Application of this method to stellar spectra observed with IUE was discussed by Brown, Ferraz and Jordan (1980).

Basically the method is as follows: The fluxes (F) in each pair of lines are related to their branching ratios, b, and probabilities of escape, q, so that

$$F_1/F_2 = \lambda_2 b_1 q_1/\lambda_1 b_2 q_2 \quad .$$

Assuming a Gaussian profile, the probability of escape is related to the opacity at line center, τ_0, by

$$q = 1 - \mathrm{erf}(\ln \tau_0)^{1/2} \quad .$$

Finally, for a Doppler-broadened line formed at temperature T_ℓ, τ_0 is related to the

mass column density, $\int N_H dh$, by

$$\tau_0 = 6.0 \times 10^{-15} \lambda(A) f_{12} M^{1/2} \frac{N_E}{N_H} \int \frac{N_1}{N_{ion}} \frac{N_{ion}}{N_E} N_H T_1^{-1/2} dh$$

where f_{12} and M are the oscillator strength and atomic weight, respectively. This method is applicable to lines of several ions such as C I, S I, O I and Fe II. (For details see Jordan and Judge 1983.)

B. Models of Atmospheric Structure

Four giant and bright giant stars have now been modeled using emission measure techniques. These are β Dra (G2 Ib-II; Brown et al. 1983), β Gem (K0 III; Brown and Jordan 1983), α TrA (K4 II) and ι Aur (K3 II), with the latter two models by Hartmann et al. (1983). The general conclusion is that the atmospheres are not extended, i.e. the extent is less than or equal to the stellar radius. Representative models of β Dra are shown in Figure 4. For this star, density-sensitive line ratios and opacity arguments suggest the 1.1×10^{14} cm^{-3} K model is appropriate for the transition region but a slightly larger scaled pressure (3.5×10^{14} cm^{-3} K) is needed to

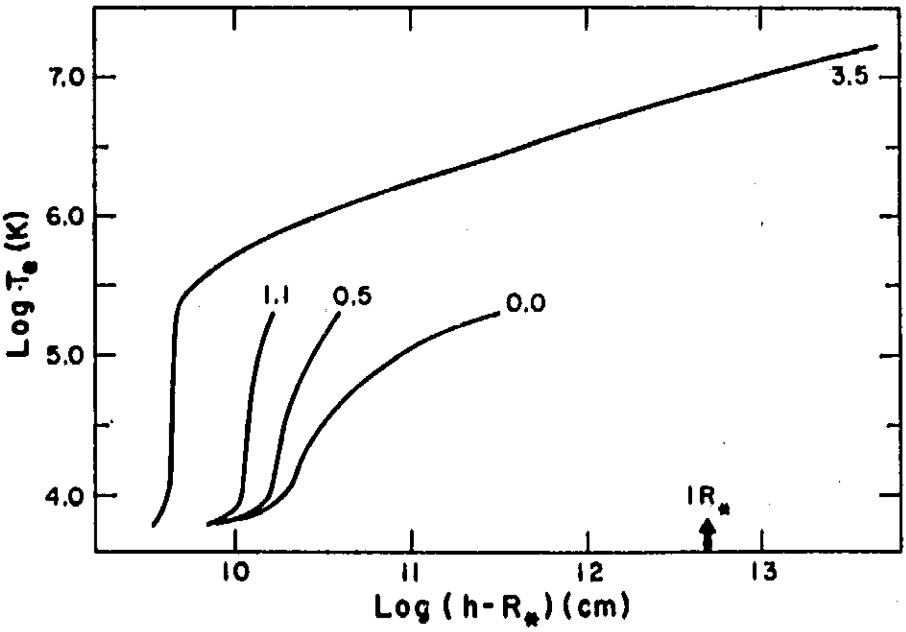

Fig. 4. Simple spherically-symmetric models of temperature versus height for β Draconis based on emission measure analysis. The scaled pressure for each model at log T_c = 5.3 is indicated in units of 10^{14} cm^{-3} K. Note that the atmospheric extent is less than or of the order of the stellar radius. Only the model at $P_0 = 3.5 \times 10^{14}$ cm^{-3} K can consistently be extended to coronal temperatures without assuming that the X-ray emitting plasma is geometrically confined (from Brown et al. 1983).

match the coronal emission, although this discrepancy can be removed by reducing the fractional area coverage of the transition region plasma. Additional evidence that the atmosphere may have more than one component is that the coronal temperature (~1.5×10^7 K) is much greater than the escape velocity of the star (~8×10^5 K) and the coronal regions must then be either magnetically confined or heated in an outflowing wind. Generally, the pressures derived for these stars are lower than those found for dwarf stars of similar spectral type. The density derived by Hartmann et al. (1983) for α TrA from the C II intersystem lines (4×10^8 cm^{-3}) is comparable to those found for extended chromosphere stars and probably reflects the density in the outflowing wind of α TrA.

Other stars have been modeled using radiative transfer codes to match the Mg II resonance line profiles including β Cet (G9.5 III; Eriksson, Linsky and Simon 1983), and β Dra, ϵ Gem (G8Ib) and α Ori (M2 Iab) by Basri, Linsky and Eriksson (1981). Comoving frame models by α Boo (K0 III) and α Ori have been computed by Drake and Linsky (1983) and Hartmann and Avrett (1983) respectively. Earlier modeling of chromospheric resonance lines was plagued by lack of constraints on the atmospheric pressure. Hartmann and MacGregor (1980, 1982) have investigated the properties of stellar winds heated and driven by Alfvén waves. However, the counter arguments of Holzer, Flå and Leer (1983) cast doubts on this mechanism for high mass loss winds. No detailed models have yet been published based on the escape probability method.

VII. EVOLUTION OF ATMOSPHERIC STRUCTURE

Our understanding of the detailed evolution of the outer atmospheric structure of cool stars is as yet fairly rudimentary. The most comprehensive study of evolutionary changes in the ultraviolet spectra of giant and bright giant stars is that of Simon (1983) in which great care was taken to separate stars ascending the giant branch for the first time from more evolved stars. Figure 5 shows the variation of C IV surface flux normalized to the stellar bolometric flux found for the stars crossing the Herzsprung-Russell gap for the first time. The normalized C IV flux rises steadily to a maximum at G0 III and then declines again. The range of C IV emission among the late G and early K giants including the more evolved stars is large, about a factor of 50, reflecting the results already mentioned concerning the Hyades giants. Additionally, Simon showed that the normalized C IV flux is well correlated with v sin i indicating, that much of the systematic change seen in Figure 5 is related to changes in the stellar rotation rates and the growth of sub-photospheric convection zones.

Although as yet too few quantitative models of atmospheric structure exist to allow the detailed evolution of stellar chromospheres and coronae to be explained, it is possible to speculate on the major factors affecting the outer atmospheres of stars evolving towards the giant branch. Gray (1982) has shown that the surface

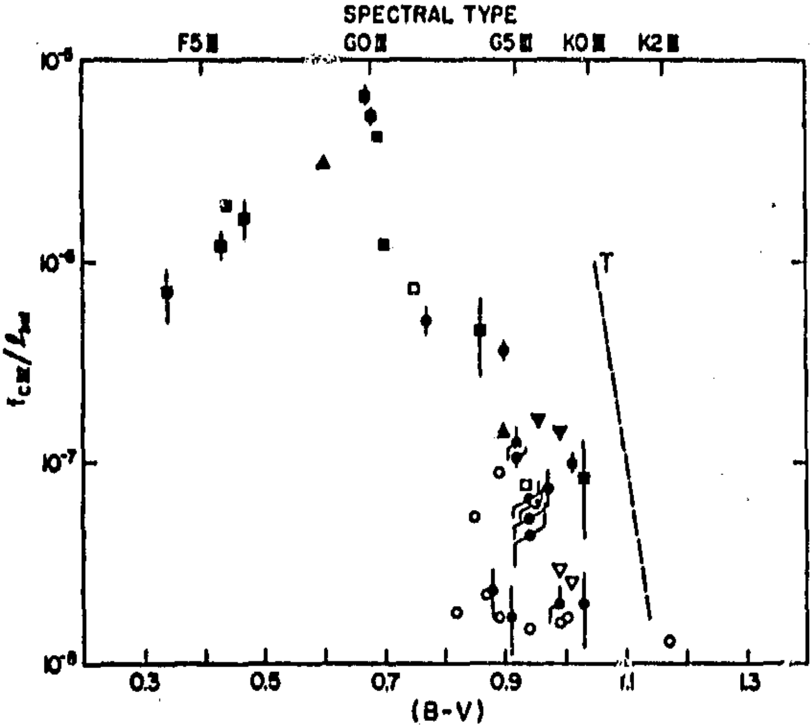

Fig. 5. Normalized C IV fluxes for yellow giants plotted versus B-V. Stars evolving up the giant branch for the first time are shown as squares while more evolved stars are shown as circles. Triangles and inverted triangles indicate the components of the Capella binary and the Hyades K giants respectively. Detections (with 1σ error bars) are plotted as filled symbols and 1σ upper limits as open symbols. The vertical dashed line shows the position of the Linsky-Haisch dividing line (from Simon 1983).

rotation rate of giants decreases dramatically and abruptly at spectral type G5. Rotation is a major factor in the generation of surface magnetic fields by the dynamo mechanism. The coronal activity level of a star that suffers a large decrease in rotation will be greatly reduced and its ability to retain magnetically-confined coronal plasma diminished. Simon, Linsky and Stencel (1982) draw attention to the systematic reduction in the temperature of the critical point of a Parker-type thermally-driven wind and the relation of this change to the cooling and expansion times of the wind. The form of the radiative power loss function of a hot plasma (cf. McWhiter, Thonemann and Wilson 1975) is such that if a plasma has a temperature between $\sim 10^4$ K and $\sim 5 \times 10^5$ K and no heating is supplied, then the plasma will cool rapidly to $\sim 10^4$ K. Simon et al. noted that the critical temperatures for β Gem (coronal) and α Boo (non-coronal) were $\lesssim 2 \times 10^6$ K and $\lesssim 3 \times 10^5$ K respectively and suggested that a lack of confined magnetic regions and the above radiative instability together could account for the lack of transition region and coronal plasma

in α Boo. This type of explanation seems reasonable given our current knowledge of the detailed properties of these stars. It is interesting to note that, because of their larger masses, the hybrid bright giants and supergiants have critical temperatures above 5×10^5 K. For example, using the stellar properties adopted by Hartmann et al. (1983) for α TrA ($\log g = 1.5$, $R = 79\ R_\odot$), the critical temperature for this star is $\lesssim 7 \times 10^5$ K.

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